Accounting for human neurocognitive function in the design and evaluation of 360 degree situational awareness display systems

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ABSTRACT

The current state and trajectory of development for display technologies supporting information acquisition, analysis and dissemination lends a broad informational infrastructure to operators of complex systems. The amount of information available threatens to outstrip the perceptual-cognitive capacities of intended operators, thus limiting their ability to effectively interact with targeted technologies. Therefore, a critical step in designing complex display systems is to find an appropriate match between capabilities, operational needs, and human ability to utilize complex information. The present work examines a set of evaluation parameters that were developed to facilitate the design of systems to support a specific military need; that is, the capacity to support the achievement and maintenance of real-time 360° situational awareness (SA) across a range of complex military environments. The focal point of this evaluation is on the reciprocity native to advanced engineering and human factors practices, with a specific emphasis on aligning the operator-system-environment fit. That is, the objective is to assess parameters for evaluation of 360° SA display systems that are suitable for military operations in tactical platforms across a broad range of current and potential operational environments. The approach is centered on five "families" of parameters, including vehicle sensors, data transmission, in-vehicle displays, intelligent automation, and neuroergonomic considerations. Parameters are examined under the assumption that displays designed to conform to natural neurocognitive processing will enhance and stabilize Soldier-system performance and, ultimately, unleash the human's potential to actively achieve and maintain the awareness necessary to enhance lethality and survivability within modern and future operational contexts.

Keywords: Situational Awareness, Indirect-vision displays, Systems engineering, Neuroergonomics, Military technology

1. INTRODUCTION

Modern advances in the development of display technologies supporting information acquisition, analysis and dissemination lend a broad informational infrastructure to operators of complex systems. Indeed, access to information, especially the ability to access the precise information that is needed at the moment that it is needed, can be considered one of the critical factors underlying the performance of operations involving complex human-system interactions. The present paper provides a conceptual discussion of system design for supporting complex human cognitive performance in challenging and dynamic environments. In specific, we examine a set of evaluation parameters that were previously outlined as a framework for assessing the utility of advanced systems supporting full-spectrum situational awareness (SA) in military environments[1]. Our aim is to incorporate greater consideration of human factors issues that, if left unconsidered, may undermine, or at minimum restrict, system utility.

Without question, the technological infrastructure that supports operations that involve high information density is advancing at an incredible pace. Such advances are rapidly forthcoming on both ends of the informational continuum. That is, as new developments in both sensor and display systems become available with regular frequency. Examples of modern display technologies that have made their way into the consumer markets include touch (and multi-touch) enabled screens, ultra-thin LED or plasma-based monitors, and graphics cards of increasing capability enabling simultaneous control over multiple graphics-intensive displays. Likewise, sensor technologies, particularly those designed to facilitate human-system interaction (for example, eye and body-motion sensing technologies for control of

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gaming and other computing applications[2,3]), are becoming increasingly advanced and integral to ongoing technology development efforts.

Such technical achievements in sensor and display technologies are currently being leveraged to increase operator productivity and safety as they work on complex tasks within dynamic and often risky operational environments. One such environment, the military battlefield, is especially in need of these advanced technologies. In particular, the ability to maintain local area security is considered critical for the modern Warfighter, who must conduct complex mobile operations across a wide variety of operational environments. Of particular concern here is the concept of *secure mobility*[4]; that is, unlike civilian mobility, Warfighters must maintain local area security through scanning of the environment and monitoring various communications and sensor feeds while simultaneously carrying out other mission-critical tasks. Moreover, because of the nature of the threats imposed by adaptive enemies that employ unconventional weaponry (such as improvised explosive devices, or IEDs), many current and future-oriented U.S. military development efforts are being designed for Warfighters to conduct operations from within heavily armored vehicles, including some that are completely enclosed. As such, the task of maintaining local area security is made more challenging by the fact that Warfighters often must achieve and maintain their situational awareness (SA) by indirect means (i.e. cameras) as opposed to direct immersion in the operational environment (i.e. with their "head out of the hatch").

2. U.S. ARMY TECHNOLOGY DEVELOPMENT

In response to the challenges described above, the U.S. Army has been modernizing systems aimed at supporting enhanced SA. It is thought that such enhanced Intelligence, Surveillance, and Reconnaissance capabilities with advanced sensors and systems will serve a fundamental role toward the facilitation of achieving and maintaining SA during the execution of future operations, particularly in complex urban settings[5]. Specifically, the ability to sustain real-time, full-spectrum SA is thought to be facilitated by technologies that provide for hemispherical (360°/90°; horizontal/vertical) visualization of the surrounding battlespace that is complimented by flexible high-resolution, narrow field of view sensors that can be slewed to any position in space near-instantaneously[6,7].

To date, the U.S. military has designed a variety of 360° SA systems for a number of both prototype and fielded ground vehicles. For example, in 2008 the U.S. Army Communications-Electronics Research, Development and Engineering Center – Night Vision and Electronic Sensors Directorate (CERDEC – NVESD) worked with industry to develop a 360°/90° hemispherical vision system for the M2 Bradley. This Distributed Aperture System, as it was named, included thirty-three color day, image intensified, un-cooled infrared sensors whose images were de-warped, stitched, and fused in real-time and then sent to three independent in-vehicle displays. Warfighters indicated that the system increased their SA as compared to the baseline Bradley; but ultimately, large-scale production was not pursued because the number and types of sensors – as well as the computational capabilities underpinning the real-time image processing and sensor fusion systems – led to prohibitive costs.

To resolve the balance between cost and capability, the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) – Ground Vehicle Robotics (GVR) partnered with CERDEC – NVESD, the U.S. Army Research Laboratory – Human Research and Engineering Directorate, and the Natick Soldier Research, Development and Engineering Center to establish a collaborative program to improve closed-hatch vehicle operations, mobility performance, and SA. This program, known as the Improved Mobility and Operational Performance through Autonomous Technologies Army Technology Objective (IMOPAT ATO), continues its efforts currently and is intent on developing a cost-effective vehicle-borne 360° SA and indirect driving system. The IMOPAT program will provide such capabilities through electro-optic indirect vision, 360° SA systems, threat-cuing sensors and algorithms, advanced crew stations functionally enabled with Warfighter-Machine Interfaces (WMIs), and cognitive workload management and monitoring systems[1,8,9]. A major projected outcome of the IMOPAT ATO is to transition the described capabilities onto the upcoming Ground Combat Vehicle (GCV), Stryker, and Mine Resistant Ambush Protected (MRAP) platforms.

In fulfilling its objectives with respect to visual SA, the IMOPAT program will create an affordable hemispherical (360°/90°) vision system with a sufficiently wide coverage area, sensible ground intercept and up-look capability, and suitable range response. To achieve its specifications, the ATO will integrate a continuous 360° field-of-view system using a limited number of visual sensors onto a gigabit Ethernet architecture that supports high-definition (HD) video transmission. Internally, the platform will have three independently controlled workstations. Despite enabling multiple workstations, designers intend to provide the capability to sustain 360° SA and simultaneous operation of other vehicle

systems from a single display. This functionality will be achieved with an advanced touch-screen WMI that takes full advantage of a large in-vehicle display. Figure 1 depicts both the external, vehicle-borne 360° SA system sensors with their respective horizontal field of view and the associated in-vehicle WMI.

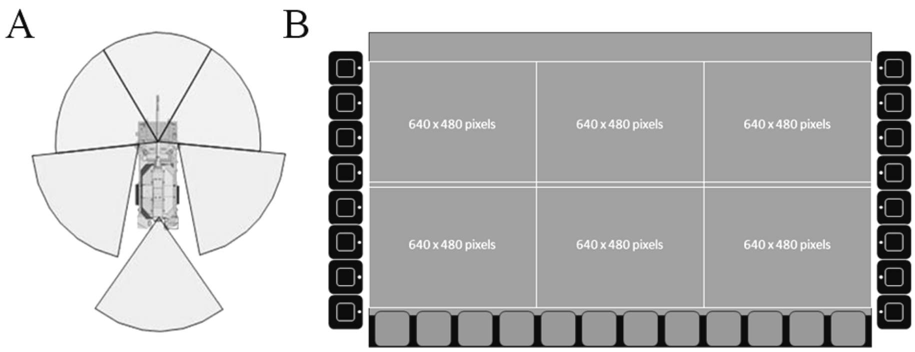

Figure 1. Illustration of some of the basic enabling technologies underlying the 360° situational awareness (SA) system being developed through the U.S. Army TARDEC IMOPAT ATO program (see text for definition of acronyms). Positioning and field of view of the external vehicle-borne sensors is shown in A, while a depiction of one configuration of the in-vehicle Warfighter-Machine Interface (WMI) is shown in B.

As shown, the 360° SA system will be enabled by six fixed field-of-view visual sensors around the vehicle. Internally, the Warfighters will have a modularly-organized display that will allow for simultaneous presentation of video feeds from all of the six visual sensors with additional functionality enabled by both hard buttons along the lateral bezel positions as well as soft buttons located underneath the video display. The screen layout will be fully configurable, allowing the Warfighter to select to view the sensor feeds in a variety of manners, from single high-resolution digital video feeds to two vertically arranged "banners" composed of up to three contiguous sensor feeds each (see Figure 1B).

As SA involves multimodal awareness of the environment[10], additional cuing technologies are to be implemented to facilitate integration of auditory and visual sensory cues. Specifically, the IMOPAT ATO will integrate sensors and algorithms to detect and locate gunfire in the surrounding environment and subsequently cue the Warfighter via their WMI display with negligible time-delay. This imagery will then be fed to the in-vehicle display allowing the operator to interrogate the location with a higher-resolution, gimbal-based sensor feed. Cuing will also be under manual control and enabled through the touch-screen; when, for example, a potential threat is noted in one of the six SA video feeds, the operator may touch the associated video feed on their WMI and the high-resolution sensor will immediately slew to that location. Finally, the ATO will demonstrate the capability to capture digital video from the vehicle's sensors onto an integrated database and it will demonstrate the ability to tag threats and log imagery within that database for future analysis as well as immediate review of recent external environmental events. Warfighters might use this capability either to rehearse missions or to identify the locations of IEDs or other potentially threatening environmental events.

3. HUMAN FACTORS CHALLENGES AND 360° SA

Despite the remarkable progress of advanced sensor systems such as those being developed under the IMOPAT ATO, as well as the current enthusiasm for capabilities afforded by modern technologies, significant questions remain regarding how to best structure information so as to enhance overall Warfighter-system performance. Of particular concern is that, while such technologies may provide expanded capabilities, the broad array of display options and informational modalities that may be provided threatens to overwhelm human perceptual-cognitive abilities, thus limiting the ability of the Warfighter to effectively interact with targeted technologies. Further, the additional tasking that follows on the coat-tails of such technical advancements may lead to a situation in which Warfighters are expected to manage an increasingly demanding and diverse array of tasks under already stressful circumstances and high-information loads.

An example of a critical human factors question that has received little attention as engineers proceed with the development of 360° SA systems is whether, given sufficient quality and amount of data, a human being is even capable of achieving a sustained, full-spectrum awareness of his or her surrounding environment, especially as that environment becomes increasingly complex and dynamic. That is, whether a human is capable of attending to and holding in working

memory many independent elements distributed throughout a 360° environment remains open for investigation. Quantitative data has thus far shown that humans may be limited in the amount of information that can be processed cognitively at any given moment in time. For instance, based on research in fundamental cognitive neuroscience, it is clear that humans are limited in processing visual information in terms of the distribution of targets throughout attentional space[11], the number of items that can be held in visual short-term memory and working memory[12], and the temporal dynamics required to process newly-received visual information[13]. Together, these basic elements of visual perception limit the ability of an individual human to actively maintain SA in a dynamic 360° environment.

Beyond basic perceptual function, investigators in the domain of SA research have identified cognitive biases and contextual factors that diminish the ability to maintain SA. For example, Endsley, Bolté and Jones[14] outlined 8 "demons" to the achievement of SA, at least half of which were associated with what appear to be cognitive biases. Research assessing SA using different display configurations in a battlefield context validated that, if presented in certain ways, humans will tend to exhibit such biases. Specifically, when using a visual display that presented environmental data from an egocentric perspective that required manual panning to obtain full 360° information, it was shown that Warfighters "tunneled into" particular aspects of the display (the forward field of view) to the detriment of attention to areas located at the periphery[15]. This cognitive tunneling was associated with poor threat detection and was manifest in reduced accuracy and slow response time. Follow-on research indicated that switching the panning requirement from one necessitating manual interaction to one that was automatic did not facilitate performance, but instead resulted in emergence of the "out-of-the-loop syndrome" wherein the operators became more passive about and overconfident in their acquisition of SA and, ultimately, performed worse at threat detection[16].

Finally, the inherent variability in and associated instability of battlefield environments requires that the criterion for successful system performance be evaluated against a diverse array of operational conditions. That is to say, the informational needs of the operator are likely to interact with the task context. For example, what a Warfighter needs in combat will certainly be different from what is needed during an extended surveillance operation. Similarly, informational needs will vary depending on whether the operation is to occur in an urban, rural, or even a jungle environment. On an even more granular level, informational needs will vary within a given operation, such as how the context differs between mission segments where the vehicle is stationary versus when the vehicle is on the move. Or, at the moment-to-moment level, informational needs can fluctuate in an instant based on the presence and recognition of a particular object (i.e. a trash pile that appears to be a location of a potential IED) or due to an environmental feature (i.e. driving past a previously difficult-to-see alleyway), thus leading to a temporary elevation of perceived threat level.

Imagine, for a moment, driving through the fictitious environment shown in Figure 2, in which the side-streets are oriented at an angle to the main axis of vehicle motion rather than having perpendicular intersections. In such an environment, something as simple as the direction of travel would likely impact our observations of system use as well as perceived threat levels. Specifically, as the vehicle approached intersections in the manner depicted in Figure 2A, we note that the most relevant vehicle sensors for threat detection would include the forward suite of cameras and that the operator would more easily anticipate upcoming potential threats. For instance, the opportunity to observe and identify whether a target was a threat would exist while approaching, entering, and moving through the intersection.

However, in the case of moving through the exact same environment, but in the opposite direction (as shown in Figure 2B), we observe a very different scenario. Owing to the angle of the intersections, it would be impossible for the operator to look down the streets upon approach and, instead, he would be constrained to examine potential threats only after entering the intersection. More to the point, in this latter case any target interrogation would need to occur using the rear suite visual sensors. This also means that the operator would be forced to look away from the direction of primary vehicle motion in order to maintain local area security. Considering the potential threat represented by the gray shaded triangle, it would appear to have greater opportunity to launch an attack on the vehicle in the scenario depicted in Figure 2B as opposed to that depicted in Figure 2A. Therefore, one would expect the level of perceived threat to appear much greater to the operator (especially a trained and experienced Warfighter) in Figure 2B. Again, this could occur simply as a function of the direction of travel through the environment. More to the point, one would expect very different use of the system in the two environments shown in Figure 2. In the situation depicted in Figure 2A, one would expect that the operator would focus almost exclusively on the forward oriented visual sensors because that was both the direction of forward motion and the direction in which most new threats would be likely to appear. In the situation depicted in Figure 2B, however, one might expect the operator to either focus exclusively on the rear-oriented visual sensors or, more likely, to toggle between forward- and rear-oriented views.

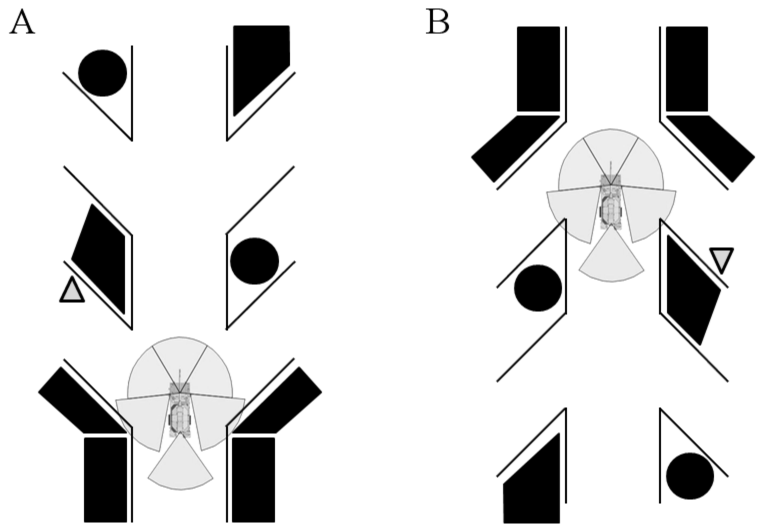

Figure 2. A fictitious environment in which one might expect a 360° visual sensor system's use to vary as a function of context and current vehicle motion. (B) is the same environment as (A), but rotated 180°. Here the shaded triangle represents a potential threat and all solid objects represent structures that would occlude line of sight. The vehicle moving along the main throughway is the same as that shown in Figure 1.

In fact, recent evidence suggests that such context factors may have a strong influence over the use of an actual 360° SA system in more typical environments. Specifically, effects similar to those discussed above were observed in an experiment in which operators were tasked with performing local area security (visual scanning for threatening humans and IEDs) while riding in a simulated vehicle through a virtual urban environment and using a prototype 360° SA system similar to the one depicted in Figure 1[17]. Despite the fact that the operators were provided with a system enabling horizontal scanning of the full 360° and that they were explicitly instructed that they were responsible for the entire field of view, they tended to focus their scanning efforts disproportionately on the forward 180° (and mostly the forward 60°; Figure 3). The interpretation of this observation, in line with previous interpretations of similar results[15,16], was that operators revealed a neurocognitive bias called "cognitive tunneling".

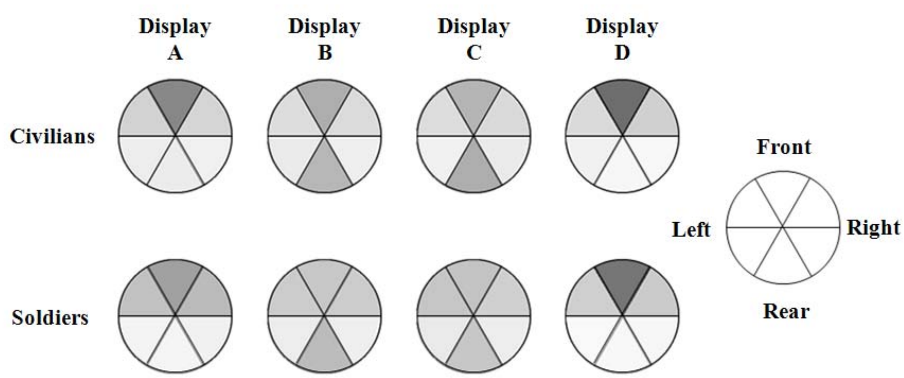

Figure 3. Proportional time spent viewing imagery from each of the six visual sensors distributed around the simulated vehicle using four different display configurations (see original work for details[17]); darker shading indicates greater proportion of time spent viewing that vehicle-relative direction.

Irrespective of the difference between the experimental environment and that used in the example in Figure 2 (i.e. the virtual city had perpendicular intersections), here we interpret this result in light of the concepts discussed above. It seems that in the presence of forward vehicle motion, a cognitive bias might appear simply because the vehicle is moving forward. This may be especially true when the task context is one of "threat detection". On a logical level, approaching a potential hazard would seem more threatening than withdrawing from one. Thus, in the context of "threat

detection" while in a vehicle moving down narrow streets of an urban environment, it would seem natural that an operator would focus attention in the most task-relevant direction – in other words, the direction in which new information is to be gained (that of forward motion) as opposed to the direction in which old information has passed.

Unfortunately, in the case of the study just described, this cognitive strategy was maladaptive. This is because threats were scripted in such a manner that they appeared for the first and only time in the rear field of view (something which could easily happen in the real-world as well). Thus, when the quantitative data were analyzed, it turned out that threat detection performance was reduced by nearly 50% for targets presented to the rear as compared with targets presented in front of the vehicle (Figure 4).

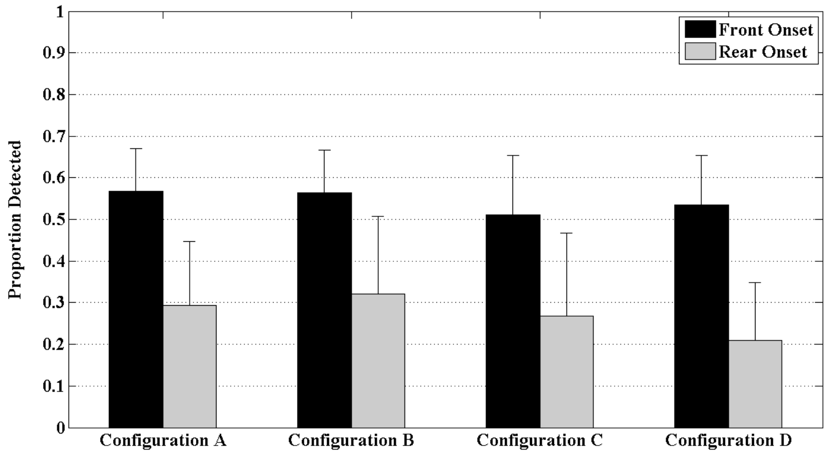

Figure 4. Proportion of threats detected as a function of a set of four different display configurations (see original work for details[17]) and as a function of location of threat onset.

Overall, then, we have several factors that must be accounted for when considering the "human dimension" of the design of complex systems. That is, in addition to system function and capability, we must consider the limitations, tendencies, and abilities of the human operator as well as the structure and nature of the environment within which the system is to be deployed and used. More to the point, we must consider the interaction between these three aspects of the overall "system" (operator – system – environment) and their fit with one another. Therefore, in the context of our current discussion it can be said that a critical step in designing and subsequently evaluating complex display systems is to find an appropriate match between display capabilities, operational needs as defined by task and context, and ultimately, by the Warfighters' ability to utilize complex streams of dynamically-changing (and often variable quality) information.

4. AN UPDATED FRAMEWORK FOR 360° SA SYSTEM DESIGN AND EVALUATION

In the remaining portion of this paper, we focus on the reciprocity between design and evaluation for 360° SA systems to be implemented in U.S. military vehicles. In particular, we examine a set of evaluation parameters that were originally identified to link current operational needs with technical specifications for the purpose of encouraging thought and discussion within the military ground vehicle 360° SA development community regarding how to best design and build solutions that meet the needs of the modern Warfighter. Rather than simply recounting what was already presented[1], however, we aim to broaden the scope of this set of evaluation parameters to more thoroughly include and account for human factors considerations on the level of behavioral tendencies and fundamental neurocognitive function. Moreover, we couch our discussion in the language of ecological psychology and cognitive neuroscience for the purpose of relating system properties to the true nature of the goals of design; that is, to adequately interface the operator, system, and the environment with one another in the most functional and adaptive manner possible.

4.1 Characterizing the operator-system-environment interaction and situational awareness

To facilitate our discussion, we first address different ways of conceptualizing the nature of the relationship between the operator, system and the environment (herein, we denote as the O-S-E fit). Figure 5 shows three of many different heuristic models that might be used to represent the O-S-E fit. Figure 5A shows what is meant to represent a classic

model that one might expect to see from an experimental psychology (or even an engineereing) perspective. In such a model, one would treat each element as an independent entity, with each having some outputs to and accepting particular inputs from the other elements. While sufficient for description of the tripartite interaction between the operator, system and environment, such a characterization assumes a degree of independence between the elements that is not necessarily justified by the real-world nature of the O-S-E fit. Although this classic view captures all pairwise two-way interactions, it completely neglects the three-way interactive relationship among the elements. A second way of conceiving of this set of relationships is shown in Figure 5B. This view, which we may call the ecological view (as it is motivated by concepts from ecological psychology), presents another intuitive and well-understood perspective and, additionally, captures all two- and three-way interactions within the O-S-E fit. This view suggests that the fundamental structure of each element is composed, in part, of its interactions with the other elements. Consider, for example, that systems are not generally designed without regard for the intended end-user or for the environment(s) within which they would be deployed.

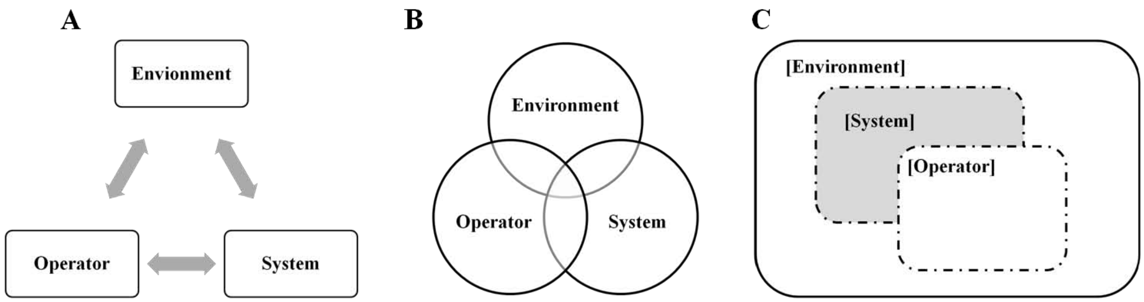

Figure 5. Three representations of the relationship between the operator, system, and the environment, what we call the O-S-E fit. (A) Shows the classical experimental psychology (or engineering) view, (B) represents the O-S-E fit as seen from the perspective of ecological psychology, and (C) shows a view from what modern psychology/neuroscience considers embodiment theory.

The third view (adopted herein), is motivated by modern concepts from both ecological psychology and cognitive neuroscience. All systems are considered to be "embodied"; meaning that their function is fundamentally adapted to the environments within which they have been developed and, more importantly, their true function *only* arises from bodily interaction with that environment[18]. Thus this view, which we will call the "embodiment view", has a fundamentally different structure from the other two. As depicted in Figure 5C, there is a primacy of the environment in the sense that any system is designed for and ultimately becomes a part of the environment within which it is embedded. Rather than showing hard distinctions between the elements of the O-S-E fit, we denote the boundaries between system, operator, and environment with dash-dot lines – indicating the relatively fluid nature of their interactions. Finally, using this type of depiction, we can imagine a variety of different configurations where, for example, the operator may be completely embedded within the system, sharing functional aspects with the system ('overlapping function') or, alternatively, where the operator and the system are completely separate but working in parallel within a shared environment.

In Figure 6, we represent the O-S-E fit as specific to the situation of vehicle-borne 360° SA systems (i.e. the operator is embedded within the system). In addition, we map the elements of the evaluation framework put forth by Mikulski and Berman[1], with some minor revisions, to the elements of the O-S-E fit. Upon first glance, we see that the evaluation appears comprehensive in that there are parameters defined to address each aspect of the O-S-E fit. In addition, we note that this depiction is specific to our situation in that the operator only interacts with the environment through the intervention of the system itself; although, the element of the evaluation that deals with neurocognitive function (neuroergonomic considerations) spans all three aspects of the O-S-E fit, indicating that the brain operates as an intermediary that simultaneously interacts with all sources of input on behavior (whether directly from the environment, through the system, or from sensory-perceptual feedback from the operator's bodily action within context).

Importantly, this means of conceiving of the O-S-E fit allows us to specify more precise relations among system elements and the overall function that they are meant to subserve – that of attaining and maintaining dynamic SA in real-time. In general, SA is thought to be a function of human neurocognitive function and it has been characterized as being composed of three inter-related but unique functions including (a) perception of the elements indicating the current status of the environment, (b) comprehension of the current status of the environment and (c) prediction (projection) of the future status of the environment[10]. The environment is present as an "ambient" influence on the system and, yet only certain elements of its state are detected by the system sensors.

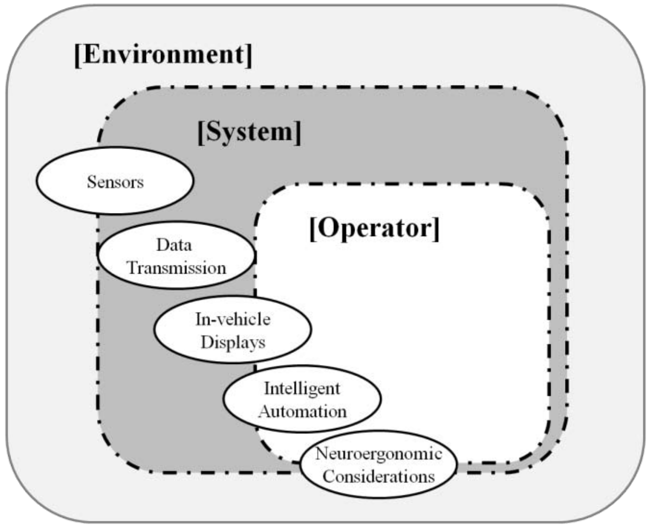

Figure 6. One possible representation of the mapping between the set of evaluation parameters for 360° SA systems and the totality of the O-S-E fit.

In Figure 7, we see the direct flow of information ("data transmission" in the language of Mikulski and Berman) as solid arrows and we see indirect, though intended, *influences* represented as dashed arrows. As shown, the only direct connection between the operator and the system is through the in-vehicle displays (specifically, the Warfighter-Machine Interface that runs on the in-vehicle displays) and the only direct connection between the system and the environment is through the system sensors. Intelligent automations are represented as being indirectly connected to the operator's neurocognitive system as they are designed to offset the above-mentioned limitations associated with perceptual, cognitive, attentional and memory processes. Finally, for the sake of completeness, we included associations among the elements of neurocognitive function that subserve SA. The forward (left-to-right) connections are presented based on logic, that is, one cannot comprehend something that they have not perceived and likewise one is unlikely to make adequate projections without at least a minimum of comprehension. The recursive connections, however, have also been suggested by basic research in psychology and cognitive neuroscience; for example, comprehension may affect perception in a recursive manner[19] and, likewise, projection (prediction) has been suggested to impact both perception[20,21] as well as comprehension[22,23].

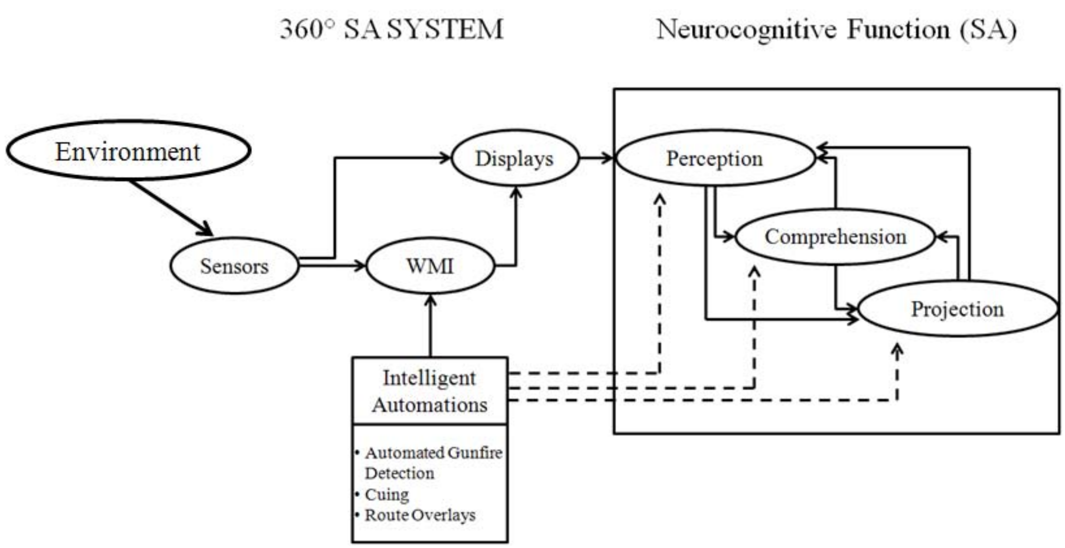

Figure 7. A more detailed depiction of the O-S-E fit representing the direct flow of information (i.e. data transmission) with solid arrows and the indirect (or intended) flow of information with dashed arrows.

4.2 Evaluation parameters for 360° SA systems

Given the above discussion, we now turn to a reconsideration of the evaluation framework proposed by Mikulski and Berman. Here, we suggest that vehicle-borne 360 SA solutions will be effective for modern combat applications as long as they adequately account for the various elements of the O-S-E fit. Factors to consider for establishing such effectiveness include breadth and stability of system capability, abilities and limitations of the operator, and the adaptive interaction of both the operator and system with the environment. To be adaptive, we must provide flexibility to allow for dynamically shifting mission goals and operator perceptions (such as those discussed in the example provided in Figure 2 above). As pointed out by Mikulski and Berman, most of the 360° SA systems that have been developed to date share several vital components, represented as “families” of evaluation parameters. These include vehicle-mounted sensors (primarily visual), data transmission systems, in-vehicle displays, intelligent automations (i.e. cuing systems), and Warfighter-Machine Interfaces (WMIs) that should be designed in accord with established human factors principles in order to account for neuroergonomic considerations. We discuss each of these families of parameters as follows.

Vehicle-Mounted Sensors. Sensor systems are the most fundamental component of any vehicle-borne 360° SA system. Indeed, as shown in figures 6 and 7, vehicle-mounted sensors often provide the only interface between the system (and thus the operator) and the environment. Adequately designed sensors enable effective detection, recognition, and identification of environmental entities from a safe distance. While the primary focus of development to date has been on visual sensors, these are often augmented by other vehicle-mounted systems that sense the environment through other modalities. Examples of additional modalities include acoustic waves, sonar, and lasers. Unfortunately, a single visual sensor cannot address the sometimes-conflicting requirements of a complete and broadly applicable 360° SA package. For instance, military ground vehicle 360° SA requirements often dictate a threshold resolution for all sensors. Yet, these same requirements also simultaneously call for wide fields of view and long range characteristics. At a fixed resolution, these requirements oppose one another; a sensor with a wide field of view inevitably maintains a shorter range and a sensor with a long range inevitably maintains a narrower field of view. Of course, given the variability in current and future theaters of operation, both characteristics are necessary. Urban and jungle environments tend to benefit less from range performance and instead require broader field of view while rural settings necessitate longer sightlines and higher resolution at distance. Balancing these two characteristics in order to meet all requirements through a single sensor may only be possible by increasing the sensor’s resolution – which may not be technologically feasible or cost-effective.

As one of the main goals of Army modernization is to maintain agility and flexibility in its military capabilities, vehicle-borne situational awareness systems must optimize for both range performance and field of view. An obvious solution would be to fabricate an ideal sensor that could simultaneously maintain long range performance while preserving a broad field of view. However, to meet the conflicting demands of these parameters, military developers have instead gravitated towards layered system solutions. In the innermost layer, developers often place a set of fixed sensors on the vehicle to obtain continuous 360° horizontal coverage. To reduce costs – and thus, the number of components – these sensors typically maintain a wide field of view at the necessary sacrifice of range performance. As such, the wide field of view sensors are particularly suited for threat detection rather than threat interrogation and identification activities. To achieve these latter capabilities, engineers develop another, outer layer to the overall 360° SA system that includes high-resolution, narrow field of view sensors mounted on pan-tilt (or gimbaled) mounts to allow interrogation of threats at a longer range. Often, these layers are augmented by an outermost layer that provides broad-area SA through networked video communication with unmanned aerial systems, unmanned ground vehicles, or other military assets.

Given these issues, the primary evaluation parameters that must be considered for vehicle-mounted sensors include those measurable parameters related to quantification of what can be seen through field of view and range performance. Therefore, Mikulski and Berman suggested that 360° SA systems be evaluated in terms of simultaneous field of view (how much of the environment can be captured at one time), sensor field of view within a given layer (how much of the environment can be captured by any one sensor at a time), range performance (defined as the maximum distance at which a target of a specific size can be discriminated), and ground intercept (providing for near-vehicle SA capacity).

Because the vehicle-mounted sensors dictate what information is available to the system and not necessarily the human (i.e. wide field of view captured images can be cropped or otherwise manipulated for presentation to the human), it can be said that the only parameter that may relate to neurocognitive function is that of range performance. In particular, one would want to specify a resolution that, at minimum, supports later display of images at a resolution equal to or greater

than that of the receptor cells within the human eye (specifically, for the display of images on the region of the retina that has the highest resolution – the central retina, where cells can distinguish stimuli down to minutes of the arc).

Data Transmission Systems. The singular purpose of data transmission within 360° SA systems is to pass information from one component to another. As shown in figures 6 and 7, this layer of the system provides the interface from the environment leading through the system to the operator via the WMI and in-vehicle displays. Modern combat platforms typically use analog data transmission systems because they tend to be highly reliable, easily integrated with the rest of platform electronics, and perhaps most important, have a low transmission latency. Unfortunately, analog models severely restrict the potential for growth of modern technologies such as 360° SA systems because they tend to have limited resolution and do not allow video processing. As such, the vehicle-mounted 360° SA development community has urged the adoption of digital video architectures which provide greater resolution and allow for image processing, which is a key capability required to augment visual displays through the WMI and to thereby enhance the Warfighters' abilities to perceive and understand the environment surrounding their vehicles.

The adoption of digital video architectures for 360° SA systems, presents new challenges that must be dealt with. For example, digital video typically requires significant bandwidth for data transmission and, as a result, also exhibits higher transmission latencies than analog video. One computational solution to this problem, real-time video compression, has not seen resounding success because real-time compression does not typically reduce bandwidth to sufficient levels and fiscal (cost) overhead. Yet, if 360° SA system interfaces are to be designed with computationally augmented visual displays (i.e. for intelligent cuing and workload mitigation discussed below), then there is no choice but to adopt digital architectures. For example, the pixel-by-pixel analysis required for intelligent threat cuing and automatic target recognition are difficult to achieve through analog video channels – as there are no pixels in analog video systems.

As should be clear from the above discussion, then, the key evaluation parameters for the data transmission include bandwidth and latency. While the previous section discussed vehicle-mounted sensors in a more general way, here the focus was on transmission of video data simply because it tends to place the largest demand on system bandwidth; control signals and other such data tend to require less bandwidth. Typical needs for video transmission can range from 200 MB/sec (for color VGA at a resolution of 640 x 480) to 1.5 GB/sec (1080p HDTV at a resolution of 1920 x 1080). Regarding latency, one of the biggest concerns relates to the neurocognitive function of the Warfighter – that is, qualitative observations have suggested that data transmission latencies above 80 ms (from sensor to in-vehicle display) tend to induce symptoms of motion sickness and other potential performance deficits whereas below 80ms, such potential detriments to performance are not as frequently observed[e.g. 24].

In-Vehicle Displays. The first level at which we begin to consider the operator-system interaction involves what information is presented to the operator (Figure 6). In-vehicle displays typically offer the most natural interface between a Warfighter and a vehicle-mounted 360° SA system. Other informational modalities, such as tactile "buzzers", exist and their potential has been demonstrated in laboratory studies[25,26]. Yet, in-vehicle visual displays are required to comfortably view and interact with video data, which is the current standard for communicating information regarding the external environment to the vehicle crew. Moreover, in-vehicle video displays are the primary way in which vehicle health indicators (i.e. fuel consumption and power management) are communicated to the operators; thus, they are particularly vital for any vehicle-based SA system. In addition to visual functions, in-vehicle displays are commonly outfitted with manual interface capabilities (e.g. touch screens) that are augmented by hard bezel buttons along their edges as shown in Figure 1B. Caution and significant human factors engineering efforts are required when attempting to develop such interfaces through the touch screen capability alone, however, because the graphic features involved will invariably require additional physical space within the WMI and they may unintentionally obscure important video data.

Because the in-vehicle display of data is such a vital component of the vehicle-mounted 360° SA system, its parameters cannot be at all disconnected from the structure of the 360° SA system itself. Using these considerations and assuming video as the primary informational modality, Mikulski and Berman thus identified screen size, screen resolution and the visibility settings (e.g. brightness and contrast) as the set of evaluation parameters for such system components. However, from a neurocognitive standpoint, it is worth noting that current thinking indicates that human information processing capacity within one sensory channel (i.e. vision) may be easily overloaded. Therefore, further investigation of how to use alternative modalities, such as the tactile "buzzers" mentioned above, is not only warranted but in fact may become critical as the density of information to be managed in complex military scenarios increases with each new technology added. Indeed research has shown that it is possible to surpass the so-called "attentional bottlenecks" created

when attempting to overuse a single modality by "substituting" sensory information from alternative sources[27]. As such, data "display" (presentation) evaluation parameters will need to co-evolve with the integration of additional modalities such as auditory and tactile informational streams.

Intelligent Automations. Sensors that operate on the vehicle-mounted 360° SA systems collect vast amounts of data and often, humans are restricted in their ability to effectively analyze that information and simultaneously perform other mission-critical operations. Thus, significant Army research and development efforts have focused on analysis of and techniques to reduce or mitigate cognitive load on Warfighters as they operate new technologies such as a vehicle-mounted 360° SA system[8,28,29]. In addition to workload reduction, the information collected from vehicle-mounted sensors may also be analyzed to cue Warfighters to potential threats to their safety. For example, such technologies could draw attention to potential enemy combatants following real-time analyses by an automated target recognition system (or another human operator) or, in a similar manner, could inform Warfighters of potential IEDs identified by analyses of previously recorded digital video. Similar applications could be applied for vehicle control, where automations could be used to identify road edges or traversable off-road terrain to mitigate vehicle rollover risks as in safeguarded teleoperation[30]. As was introduced in the discussion of in-vehicle displays, the multisensory nature of human perception could also be exploited. For example, cuing technologies could be multi-modal, perhaps in notifying Warfighters of threats with auditory and/or tactile alerts.

Unfortunately, intelligent cuing technologies are often rendered unreliable because they analyze information from noisy sensors in dynamic, unstructured environments for which their underlying mathematical or statistical models might not have been formulated. Consequently, intelligent cuing often maintains a high rate of false alarms combined with low probabilities of correct detection[31]. Therefore, it becomes highly likely that, faced with the choice of basing decisions on demonstrated unreliable information, Warfighters would ignore or disable such automations for the more proven techniques of relying on their own eyes and ears. Indeed such disuse behaviors have been shown in other contexts of human use of automation[32]. Therefore, any effort to transition intelligent cuing technologies to fielded vehicle systems must account for critical usability issues.

Additionally, intelligent cuing technologies often incur heavy computational loads. The need to analyze large amounts of data and to run computationally-intensive algorithms in real-time dictates a concurrent need for an integrated digital data transmission system. Recalling our prior discussion of data transmission requirements and the heavy reliance on digital video architectures in 360° SA systems, the computational cost of such algorithms must also be weighed in light of the overall latency of the 360° SA system. That is, such algorithms may drive total latencies beyond acceptable limits, unbalancing an already tenuous relationship between bandwidth utilization and information presentation.

Despite current challenges to their implementation, the military still believes that investing in intelligent cuing technologies can provide enormous potential benefits to combat and other operations. Thus we consider their inclusion in 360° SA systems of the future and therefore, they must be evaluated against reasonable parameters. As shown in Figure 6, we note that although intelligent cuing is a technological capability provided by the system, assessment is largely driven by the needs of the operator with respect to its usability. Thus, considering the cognitive behavior potential of Warfighters with respect to intelligent automations (i.e. the potential for disuse or even misuse of the technology) the identified evaluation parameters include estimators of overall reliability and validity of system outputs (primarily we look to probability of correct detection and false alarm rates) as well as systems-level issues such as computational efficiency and feasibility of model implementation in software.

Neuroergonomic Considerations. As described throughout this discussion, vehicle-mounted 360° SA systems are incredibly complex and the cognitive loads required of Warfighters during the analysis and control of 360° SA subsystems must be reduced or managed through the development of effective Warfighter-Machine Interfaces (WMIs). WMIs are often designed for in-vehicle displays to control and analyze information from vehicle-mounted visual sensors, but other modalities may be employed to provide primary or redundant capabilities alongside in-vehicle displays. For instance, yolks or keyboards may be utilized to control pan-tilt mechanisms or audible messages may be developed to provide redundant threat cuing and localization capabilities. WMIs may be built in various manners but they must be developed in accordance with established human factors principles that simplify, or at least lend efficiency to, a Warfighter's interaction with the vehicle-mounted 360° SA system.

One of the challenges faced in the design process for evolving military systems is uncertainty about how well they will provide for the complex cognitive operations that the Warfighter must execute during risky and time-pressured missions.

In general, advanced systems are designed by software, systems, and human factors engineers based on *a priori* assumptions or on *a posteriori* assessments of usability in specific environments. Frequently, such assessments are based on tasks that are either too limited to be operationally relevant or are too complex to allow for precise scientific inference regarding generalized behavioral tendencies. Moreover, such assumptions and assessments often neglect consideration of how humans naturally process information within their neurocognitive system. The typical assumption underlying system development is that, other than providing assurances for functionality, the uncertainties regarding usability can be countered by allowing sufficient time for operators to learn how to use the system. Yet, one objective of military development is to create interfaces for which the time required to train operators is minimized[33].

Neuroergonomics is an emerging area of investigation, spawned by research and theory in disciplines such as ergonomics and neuroscience, in which the objective of research is to understand how the human brain functions in complex, real-world environments[34]. Neuroergonomic design, then, is centered on creation of tools and interfaces that naturally compliment the user, using design principles rooted in the natural processing capabilities of the neurocognitive system. Recently, the U.S. Army has taken interest in the integration of theory and practices from cognitive neuroscience and neuroergonomics in that they may lead to development of systems that will improve and optimize Warfighter-system performance in real operational scenarios while minimizing training time needed to gain proficiency[33].

Fortunately, considerable research in human factors, psychology and cognitive neuroscience have brought about the development of standard metrics and advanced the application of mathematical modeling to assess the effectiveness of WMIs in terms of human behavior and neurocognitive function. Many of these metrics and models aim to determine the ease and quickness with which a Warfighter interacts with system capabilities, as well as assessing and understanding how different display and informational conditions impact the function of the operator's nervous system. Traditionally, such assessments required verification through extensive qualitative user evaluations that were subject to variations in individual tastes, interests, and capabilities. However, more recent Army efforts have begun to bring scientific rigor back into the assessment of complex systems in complex environments[35]. As the science progresses in this direction, it becomes increasingly possible to add to our understanding of how to evaluate the effectiveness of WMI for complex military applications. Examples of evaluation parameters that would prove useful include, but are unlikely to be limited to, measures such as probability of correct threat identification, optimality of movement parameters required for interface interaction (i.e. movement time vs. reaction time), time to comprehend presented information, optimality of speed and accuracy of decision making, as well as assessments that require more advanced data collection and analysis, such as understanding how to induce recruitment of proper task-specific brain regions and maintain adequate physiological levels (i.e. arousal) and attentional levels to optimize mission performance.

CONCLUSION

In this paper, we have presented and discussed the complex topic of providing display systems adequate to support the acquisition and maintenance of 360° situational awareness (SA) in dynamic military vehicle environments. In so doing, we have reviewed two examples of systems that have been developed by U.S. Army scientists and engineers, alongside industry partners, one of which is still the focus of a current Army program (TARDECs IMOPAT ATO). In order to motivate our discussion of evaluation parameters suitable to stand as criterion for assessing the quality and capability of 360° SA systems as they are matured, we then discussed a variety of human factors challenges to the systems developers. The ultimate point of focus for this discussion was to emphasize the need to take a broad view on understanding how to design an optimal system to meet the needs of the modern Warfighter; that is, we concluded that the need rests in optimizing the fit between display capabilities, operational needs as defined by task and context, and ultimately, by the Warfighters ability to utilize complex streams of dynamically-changing information – in the shorthand of the current paper, we called this the operator-system-environment fit. In the end, we reviewed and revised a set of evaluation parameters that were previously put forth to unite all interested stakeholders under a common framework to ensure that 360° SA systems continue to provide Warfighters with the ability to generate sound decisions in combat. Informed by elementary concepts and data from studies in human factors, psychology and cognitive neuroscience, our overall aim was to enhance the understanding of the relatively critical nature of considering the interaction between the operator, system and environment as *the* essential ingredient to advancing systems of sufficient quality to enhance lethality and survivability of the Warfighters of today and those of years to come.

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